AERODYNAMIC ANALYSIS OF FLAPPING WING

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Abstract:

Desire to attach wings and fly like birds had been an age old desire . Many efforts towards this fantasy failed in the past except for limited success by Otto Lilienthal and Sir Langley towards the end of 19th century which brought a full scale vision by the efforts of Wright-brothers on a fixed wing aircraft. Since then many developments took place in this field inclusive of rotary wing and jet age. But the primitive question on aerodynamics of natural flight(how does a bird fly and why does it in this way?) remained an intriguing one, which compelled the aerodynamicists to probe into the insight. The need for the study of an ornithopter is based on the argument that flapping wing flight, at small scale, is more efficient than traditional fixed wing and rotary flight. Flapping wing flight more closely mimics natural flight and has potential for being lower in weight and having greater endurance. Recent approaches involve analyzing bird, bat and insect flight which enabled understanding of the mechanisms that biological 'machines' that use flapping to provide lift and thrust. It is known that the flexible nature of membrane type wings can increase aerodynamic stability by damping unsteady forces/moments and storing elastic energy. The objective of this study is to analyze relative merits of a flapping wing over a fixed wing. This paper primarily focuses on the role of wing flexibility in flapping wing flight. The study of two wings, various flapping frequencies and air flows will help future researchers in perhaps eventually building a flapping wing UAV with flexible membrane wings.

Keywords: *Ornithopter, flapping wing, fixed wing, endurance, flexibility , aerodynamics, stability*

NOMENCLATURE:

AR	Wing Aspect Ratio
c	Aerofoil chord
C_l	Lift coefficient
L	Lift
W	Wing loading
U	Flight speed
V	Relative flow velocity at ¼ chord
ρ	Atmospheric density
ψ	Flapping angle
ζ	Azimuthal angle
θ	Feathering angle
Θ_s	Elevation angle

1.0 INTRODUCTION :

Over the past twenty-five years, interest in small-unmanned aerial vehicles (UAVs) has greatly increased. Most of the UAVs in production and use today are fixed wing airplanes, which means that these aero planes employ traditional methods of lift and thrust: a propeller for thrust and rigidly attached wings relying heavily on the free stream velocity for lift. Tasks of these vehicles include surveillance, communication relay links, decoys, and detection of biological, chemical and radiological materials. However, there is another realm of UAVs that is just beginning to be explored, those which utilize flapping wings. These types of vehicles are also known as ornithopters.

2.0 DEVELOPMENT OF ORNITHOPTER:

Need for the development of an ornithopter is based on the argument that flapping wing flight, at small scale, is more efficient than traditional fixed wing and rotary flight. Flapping wing flight more closely mimics natural flight and has potential for being lower in weight and having greater endurance [1]. In addition, strategic and stealth applications for flapping wing vehicles are evident as well, as they mimic natural flyers and could steal their presence. Thus, flapping wing air vehicles may provide a significant advantage over their fixed-wing counterparts [1] specially in tactical military applications.

3.0 RECENT ANALYSIS OF VARIOUS MECHANISM:

In analyzing natural flyers, the issue of wing flexibility has emerged, since many insect and bird wings have complex elastic structures. The flexible nature of membrane type wings can actually increase aerodynamic stability by damping unsteady forces/moments and storing elastic energy [2]. While some vehicles and mechanisms that utilize flapping wing flight have been demonstrated [3], few have been successful.

4.0 OBJECTIVE OF THE STUDY:

The objective of this paper is to highlight salient aspects of flapping wing and analyze different advantages of this over fixed wing mechanism.

5.0 GENESIS:

It was mankind's fascination with bird flight which originally evolved the discipline of aerodynamics[2]. In the earliest stages of developing flying vehicles, it was discovered that separating the mechanisms for lift and thrust was the easiest and quickest way to become airborne, thereby freeing the earliest engineers from the fruitless attempts at mimicking animal flight [3]. Flapping wings have been thought to be more efficient, maneuverable, agile and stealthier than fixed wings. Hence researchers explored the field of natural flight aerodynamics.

6.0 WING MOTIONS:

Azuma (1992) identified four fundamental motions of a beating wing.

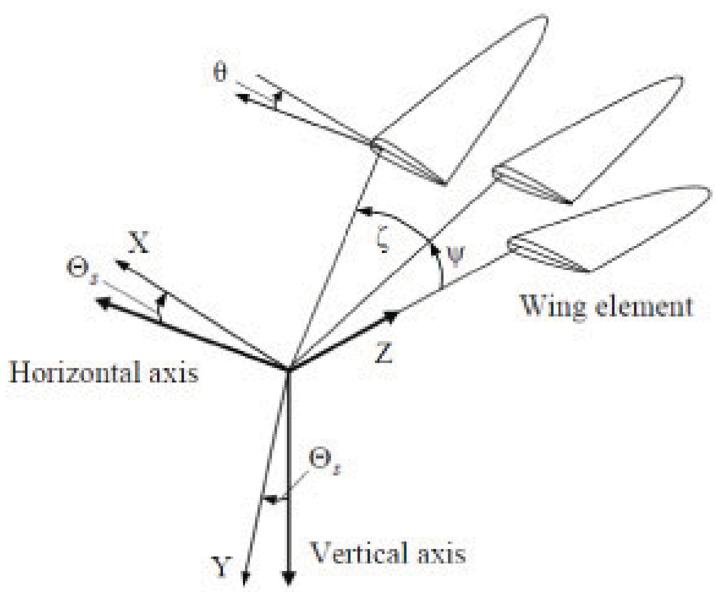

Figure 1: Wing beating motions. Sketched from Azuma (1992)[4]

1. An out-of-plane motion called "flapping" (flapping angle ψ);
2. An in-plane motion called "lagging" (lag or azimuthal angle ζ);
3. A twisting motion of the wing pitch called "feathering" (feathering angle θ);
4. An alternatively extending and contracting motion of the wingspan called "spanning."

The stroke plane is defined by the elevation angle, Θs. The feathering motion is also called "supination" for positive pitch and "pronation" for negative pitch. Insects employ the same fundamental wing motions, except for spanning, since the structure of the insect wings do not allow it.

7.0 IMPORTANCE OF WING LOADING:

Wing loading can be defined as the ratio between the weight of the flying object and the wing area. The standard values usually chosen for these two numbers are the maximum gross weight and the projected area of the wings on a horizontal plane. Wing loading can be expressed as :

$$L = W = \tfrac{1}{2}\rho U^2 S C_L \Rightarrow W/S = \tfrac{1}{2}\rho U^2 C_L.$$

where L is the lift force, r is the local air density, U is the forward flight velocity, and S is the wing plan form area. In level flight the lift force equals the body weight, W.

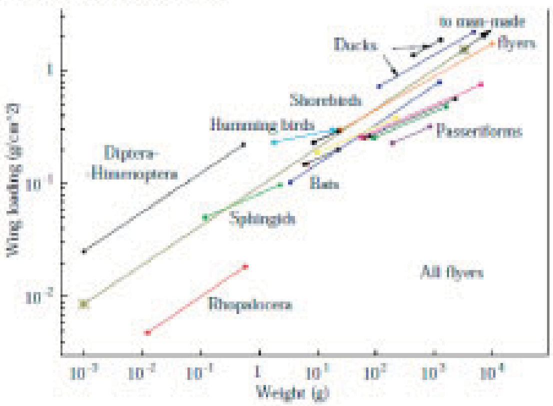

Fig 2: Wing loading of insects and birds versus weight ranging from 1mg to 1 kg. Adopted from Greenewalt [5]

In Figure 2, above the weight ranges from 1mg for small insects to 1 kg for heavier birds. Even though the data is more scattered, the slope of the interpolating straight line remains about 0.33[5] .As a matter of fact, if the fitting line that passes through the two star symbols is prolonged toward the right (heavier flyers), wing loading of almost all natural flight are covered.

8.0 LIFT GENERATION IN FLAPPING WING FLIGHT:

For a comprehensive understanding of flapping wing flight, it is necessary to observe when and how lift is generated during a flapping cycle. A typical cycle in the flight of a flapping wing vehicle consists of a down stroke and an upstroke (Figure 3). Lift generation on the various strokes of a flat rigid plate have been studied by Hong et al. [6]. Assuming the wing starts from a maximum height position ,

- **Start Of The Down Stroke:** The lift starts to increase due to vertical air reaction.
- **Actual Down Stroke :** The aerodynamic force peaks .
- **End Of The Down Stroke :** The lift force starts to decrease.
- **Actual Upstroke :** Aerodynamic forces create negative lift as the wing travels upwards.

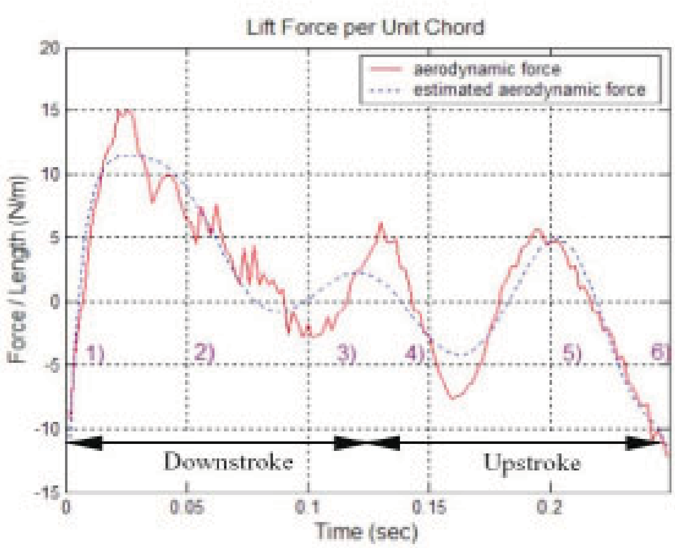

Fig 3: Unit Force vs. Time for Up and Down Strokes [6]

9.0 THRUST GENERATION IN FLAPPING WING FLIGHT:

In natural flyers, it has been shown that insects take advantage of unsteady aerodynamic phenomena to generate thrusts. The generation of thrust can be broken into 4 parts [6]:

- **Start of Downstroke:** The wing translates with a fixed collective pitch angle.

- **End Of The Down Stroke:** The wing turns so that the blade angle of attack is positive on the upstroke.

- **Actual Upstroke:** The angle of attack is still positive here.

- **End Of The Upstroke/Beginning Of The Down Stroke:** The wing's angle of attack changes from positive to negative.

Figure 4 shows the lift and thrust generation with respect to the phase of a flapping airfoil [8]. The wing starts at a point, labeled as 18°, and then proceeds to complete one full flap (traveling 360°) and returning to its starting position. The arrows point the direction of flapping force which on vector resolution split into lift and thrust force. In one cycle of 3Hz frequency, the net lift gain is seen zero so the height of flight is fixed with the net forward thrust.

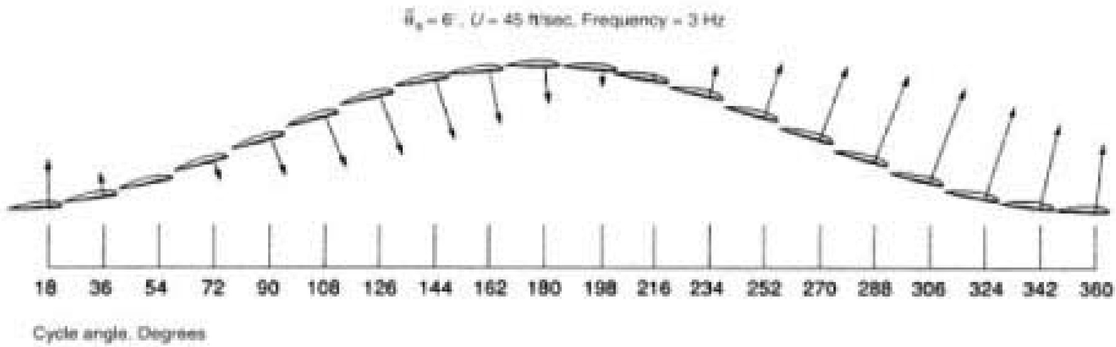

Fig 4: Lift and Thrust Generation vs. Phase [7]

10.0 POWER TO FLY :

The power necessary to achieve flapping flight can be calculated by using formulas derived by Azuma2, 1992[4] and the equations are plotted in the graphs shown below. This power is mainly a function of the following variables: vehicle mass, flapping frequency, forward speed, wing chord, wing span, and wing beat amplitude. Example calculations for a vehicle weighing 50g and having an ideal 100% efficient Reciprocating Chemical Muscle (RCM) are given.

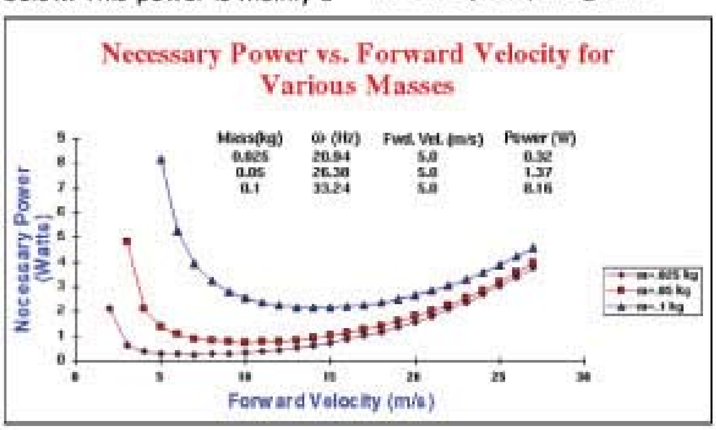

Fig 5: Graph of necessary power vs. Forward velocity for Various masses.[8]

Based on this analysis, approximately one watt of power would be necessary to propel an ornithopter of 50 gm at 5 m/sec. For comparison, several plots of the necessary power versus forward velocity and mass are provided in Figure 5.Doubling the mass of the ornithopter results in almost eight times the required power.

11.0 FLEXIBLE WINGS VERSUS RIGID WINGS:

It has been shown that flapping wing based UAVs have certain advantages compared to their fixed wing counterparts:

(a) Ability to hover, react more efficiently to gusts, have lower weight, and generate lift without excessive size and weight [9].

(b) Flexible wings have also been shown to be more advantageous than rigid wings, with having higher stall angles by performing adaptive washout, and providing smoother flight.

(c) The main advantage of flexible wings is that they facilitate shape adaptation, essentially adapting to the airflow to provide a smoother flight . A wing changes shape as a function of angle of attack and wind speed [9]. This adaptive washout is produced through extension of the membrane and twisting of the structural members, resulting in angle of attack changes along the span of the wing in response to the oncoming flow [10].

(d) With a decrease in relative airspeed, the angle of attack of the wing increases, and the wing becomes more efficient, resulting in near constant lift. This enables a UAV with flexible wings to fly with exceptional smoothness, even in gusty conditions.

12.0 RECOMMENDATION:

Due to the aerodynamic advantages of flapping wing over wing, more studies should continue across the globe for further reveal its more advantages and aspects. It is just a starting approach. Due to the limitation of lab facilities and financial problem further studies could not be continued. But regarding the huge prospect of this topic, we are looking forward to do further aerodynamic analysis of flapping wing and its approach to practical aviation world.

13.0 CONCLUSION:

Lift and thrust generation of a conventional flight is well established in classical aerodynamics. The flapping wing is a specialized breed of flying machines that mimics the natural flyers. As such, these special flights need a focused approach to analyze aerodynamic aspects of natural flight. Various researches and studies in this field highlighted that a flexible wing of an ornithopter is highly adaptive and elastically resilient while adding thrust in flapping motion, which reduces the power consumption and indicative of high propulsive efficiency. However, the mechanical linkage and complex mechanisms for flapping system poses limitation in extensive use of ornithopters in general aviation use. With the advent of advanced technologies, easier and simple systems may evolve with light weight flexible wings that can become a conventional flying machine of the future with additive stealth dimension.

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